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Advances in Three Dimensional Reversible Photonic Modules for Phased Array Control

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ABSTRACT

Novel three dimensional multichannel high speed N-bit switched grey-scale optical amplitude and phase control modules are described. These modules rely on high speed binary on/off optical switches arranged in serial cascaded architectures with preset optical attenuation and/or phase settings provided by relatively slow speed but programmable optical devices and passive polarization optics. Modules have both collinear in-line and non-collinear symmetrical optical designs to improve optical signal stability and minimize optical path difference delays, respectively. These modules can be used for analog microwave and millimeter wave signal processing applications such as array antenna beam steering, beam nulling and adaptive beamforming operations.

2. INTRODUCTION

We have proposed and demonstrated various multi-channel three dimensional (3-D) photonic modules based on polarization optics for both narrowband phase-based phased array antenna control [1-2], and wide instantaneous bandwidth time delay-based phased array antenna control [3-5]. These modules can perform a variety of signal processing operations such as signal gain and phase control, and signal true-time delay control, as required by high performance antennas and radars. Furthermore, these modules can be used for transmit/receive optical phased arrays in optical communications, and recently we have proposed several photonic modules for ultrashort phase/time delay coherent optical arrays, such as used in coherent laser radar arrays [6]. Using polarization optics, we have shown grey scale (> 6 bits) amplitude and phase control for radio frequency (rf) signals [7] using moderately fast (e.g., 1 ms) switching speed programmable nematic liquid crystal (NLC) devices [8]. Grey scale optical beam control via NLCs is possible because of the analog nature of the NLC molecular rotation process when subjected to a variable applied electric field. For advanced radar applications, it is highly desirable to have faster switching N-bit optical control modules. Present-day commercial ferroelectric liquid crystal (FLC) devices show at least an order of magnitude faster (e.g., 35 μs) switching speed than NLC devices [9]. Nevertheless, FLCs exhibit material intrinsic optical switching bistability and therefore cannot directly provide grey scale optical amplitude and phase modulation. Hence, indirect methods have been proposed for achieving grey-scale optical amplitude and phase control using binary devices such as FLCs. One approach used to provide grey-scale optical amplitude control is spatial averaging or multi-pixel area modulation where several device pixels are used to form one grey-scale macro-pixel [10]. This scheme uses up valuable device space-bandwidth product. Another approach used to provide grey-scale optical amplitude control is via temporal averaging. In this case, a time averaged response of the light being modulated by the binary device over several on and off cycles gives the desired grey-scale response [11-12]. This method is particularly restrictive for antenna applications where the light is already being modulated by high speed rf and microwave signals. Hence, slower optical switch modulation cannot be tolerated, except for antenna beamforming. Attempts to achieve indirect optical phase modulation using these fast but binary FLCs have also been made where several FLC devices with fixed but different retardations were cascaded with waveplates and polarizers. These methods are highly dependent on being able to accurately match modulator designs to device fabrication constraints, and are accompanied by phase dependent optical amplitude modulation [13].

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Recently, for the first time, we have shown how slower speed grey-scale NLC devices and faster speed binary FLC devices can be cascaded to form high speed N-bit rf signal amplitude control optical devices [14-15]. In this paper, we will further extend the theme of the earlier joint NLC-FLC work to show how other high speed 3-D N-bit photonic control modules can be formed for both amplitude and phase (or ultrashort time delay) control using a combination of high speed binary optical devices and slower speed grey scale optical devices. The motivation for using 3-D optics includes increased channel packing density and reduced optical interconnection complexity, particularly when compared to integrated-optic and all-fiber modules.

3. BASIC ARCHITECTURE FOR HIGH SPEED OPTICAL CONTROL MODULES

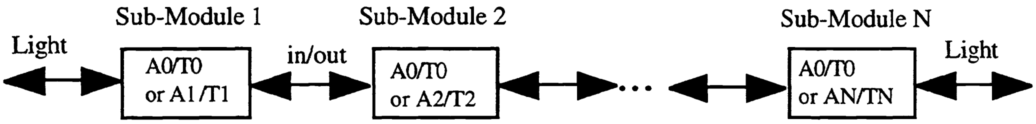
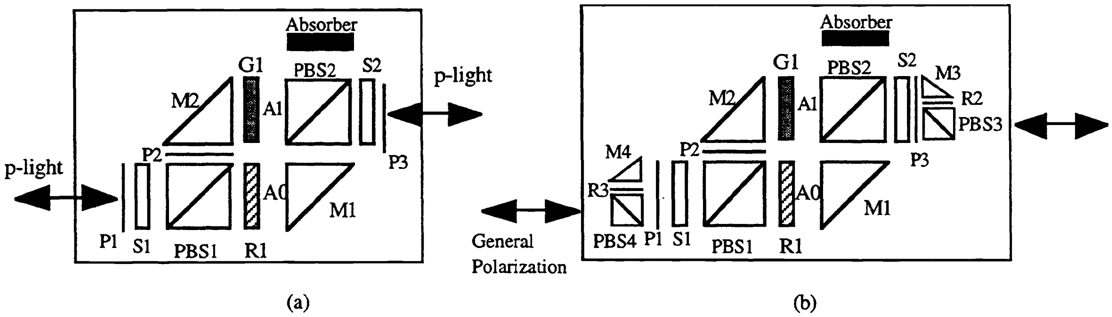


Fig.1 Basic high speed reversible N-bit optical control module architecture formed by cascading N control sub-modules. Each sub-module uses high speed binary on/off optical switches and slower speed programmable grey-scale optical devices.

Fig.1 shows the basic architecture for the construction of our proposed N-bit optical control modules. As an N-bit amplitude control module, the optical attenuation provided by the nth bit control sub-module is An or Ao, where An is the preset active attenuation when the nth bit sub-module is on, and Ao is when the sub-module is off. Thus, by appropriately switching the N high speed sub-modules, it becomes possible to generate N-bit grey scale optical beam amplitude control. The same basic principle works for the N-bit grey scale optical phase (0-2π) or time delay control. In this case, the preset optical attenuation settings are replaced by preset optical phase/time delay settings T1/T0, T2, T0, etc. Both non-collinear symmetrical sub-module designs and collinear in-line designs are introduced, and their tradeoffs related to channel packing density, module assembly, and signal processing stability are discussed.

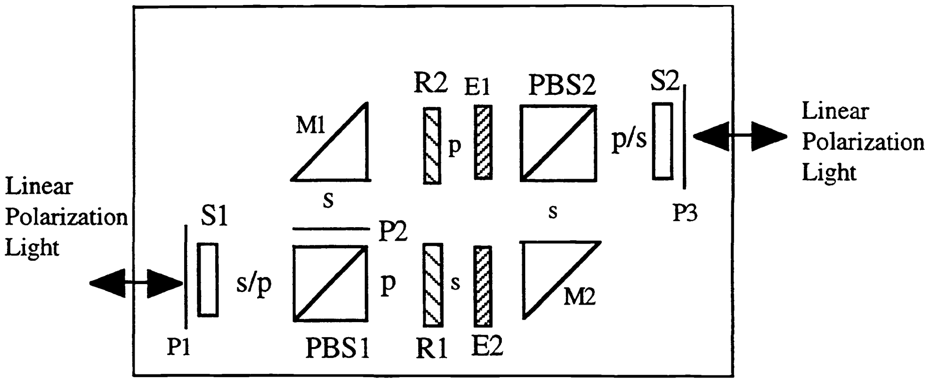
4. HIGH SPEED N-BIT NON-COLLINEAR SYMMETRICAL MODULES



S's: High Speed on/off planar optical switch
P's: Polarizers
R's: 90 deg. linear polarization rotators (programmable or fixed)
G's: Grey-scale linear polarization rotators (programmable or fixed)
M's: TIR prisms or 45 deg. mirrors
E's: Grey-scale optical phase/time shift programmable devices

Fig.2 A nth bit reversible optical attenuator sub-module for (a) linearly polarized input light and (b) general polarization input light.

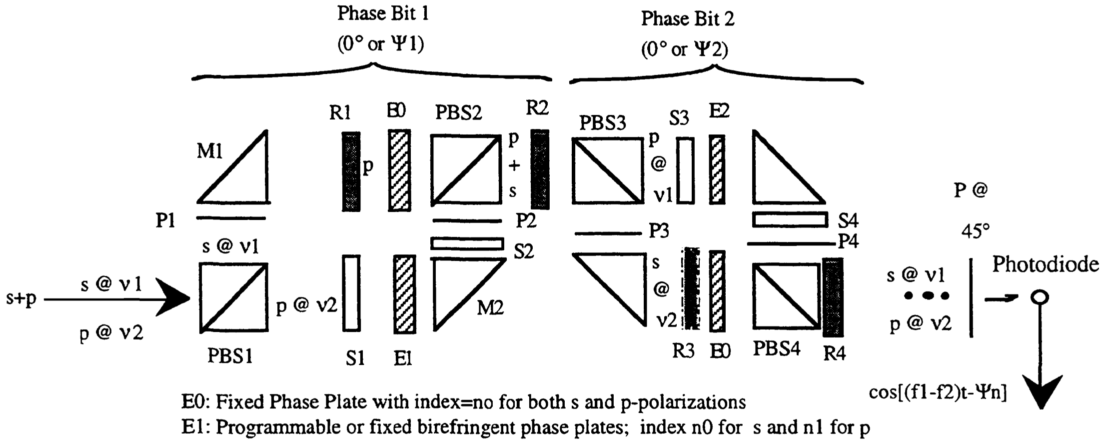
Fig.2 shows a proposed high speed nth bit optical attenuator sub-module using polarizing beam splitters (PBS's) cubes, polarizers (P's), high speed binary optical switches (S's) such as FLC devices, total internal reflection (TIR) prisms or mirrors (both labelled by M's), and 90 degree linear polarization rotators (R's) such as halfwave plates, twisted or parallel-rub NLC devices. Fixed but variable power optical linear polarization rotation devices (G's) such as programmable Faraday plates or programmable twisted or parallel-rub NLCs are used for the optical attenuation controls A0 and An for the nth sub-module. This notation is followed for all designs shown in this paper.



E1,E2: Programmable NLC Phase Cells or Fixed Thick Glass Plates

Fig.3 nth bit reversible optical phase/time delay sub-module for linearly polarized input light.

Fig.3 shows a high speed nth bit optical phase or ultra-short optical time delay control sub-module. Accurate optical phase shift is introduced via the use of preprogrammed and fixed parallel-rub birefringent-mode NLC devices labelled by E's, that act as electrically programmable analog optical phase plates.



E0: Fixed Phase Plate with index=no for both s and p-polarizations
E1: Programmable or fixed birefringent phase plates; index n0 for s and n1 for p
E2: Similar to E1 but with index n2 for p

Fig.4 High speed N-bit optical phase shifter for two frequency, orthogonal linear polarization laser inputs, such as applied in optical beamforming systems using heterodyne detection.

Fig.4 shows an N-bit optical phase shifter set-up that is suitable for applications where the input light contains two orthogonally polarized (s: vertical; p: horizontal polarization) light beams with different optical frequencies that are mutually phase coherent. This type of system can be used for narrowband modulo-2π optical or electronic phased array systems where optical phase (or short time delay) control is required. Within each phase bit sub-module, there are two switched phase settings, where one setting gives a relative zero phase shift between the two beams and the other setting gives the desired fixed relative phase shift. A photo-diode via hetrodyne detection generates the desired intermediate frequency signal with the desired radio frequency (rf) phase set by switching the binary optical switches in the appropriate high speed sub-modules.

5. HIGH SPEED N-BIT COLLINEAR IN-LINE PHOTONIC CONTROL MODULES

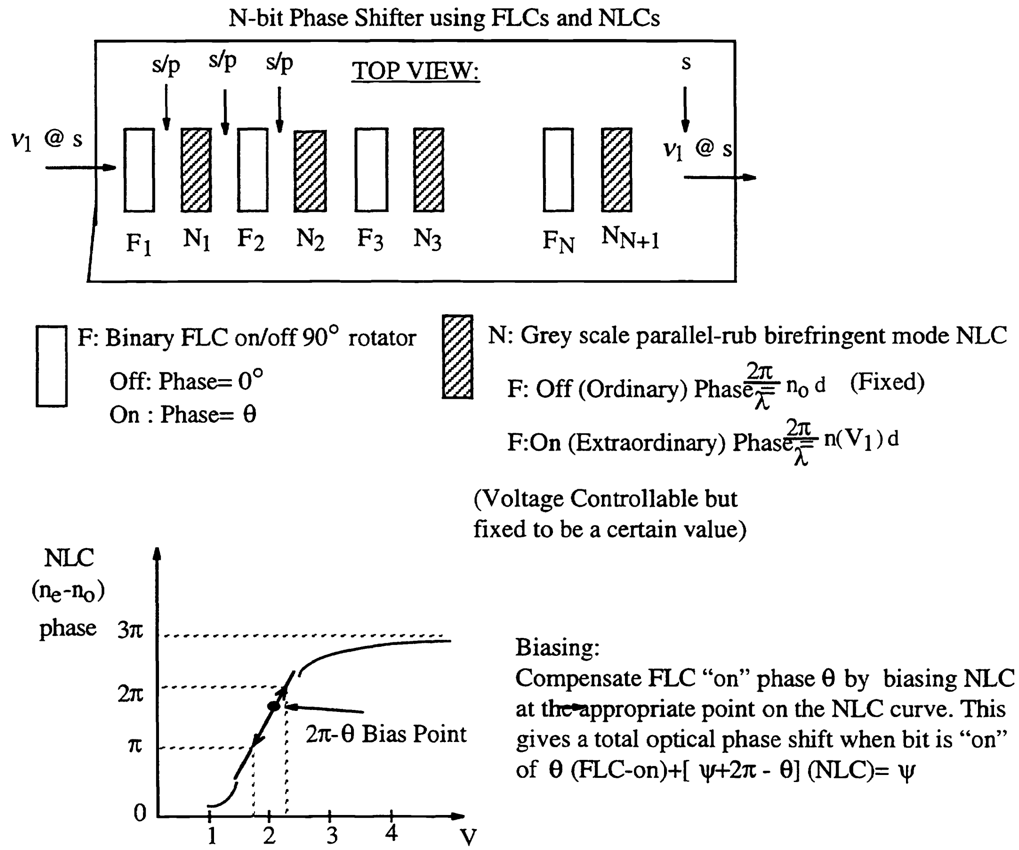


Fig.5. The reversible ultra-thin broadband in-line N-bit high speed optical phase shifter.

The previous modules were based on cube PBSs that resulted in non-collinear module designs. In some cases, higher module compactness and greater optical robustness is required. This can be achieved through in-line optical designs. Fig.5 shows an ultra-thin broadband modulo-2π optical phase shifter design using a casacade of ultra-thin FLC and NLC cells labelled F's and N's, respectively, for clarity of operations. A typical individual cell thickness including the encapsulating glass plates is 2 mm. Using thin-film deposition and laser surface micromachining techniques, a typical 6 bit optical phase shifter could have a 5 mm total thickness, hence making a compact and robust ultra-thin device. Notice that proper biasing is required for the NLC devices because the FLC devices introduce an additional phase shift when they are turned on. This phase shift can be cancelled or compensated using appropriate placement of the NLC director to get negative phase shifts and by electrically biasing the NLC cells.

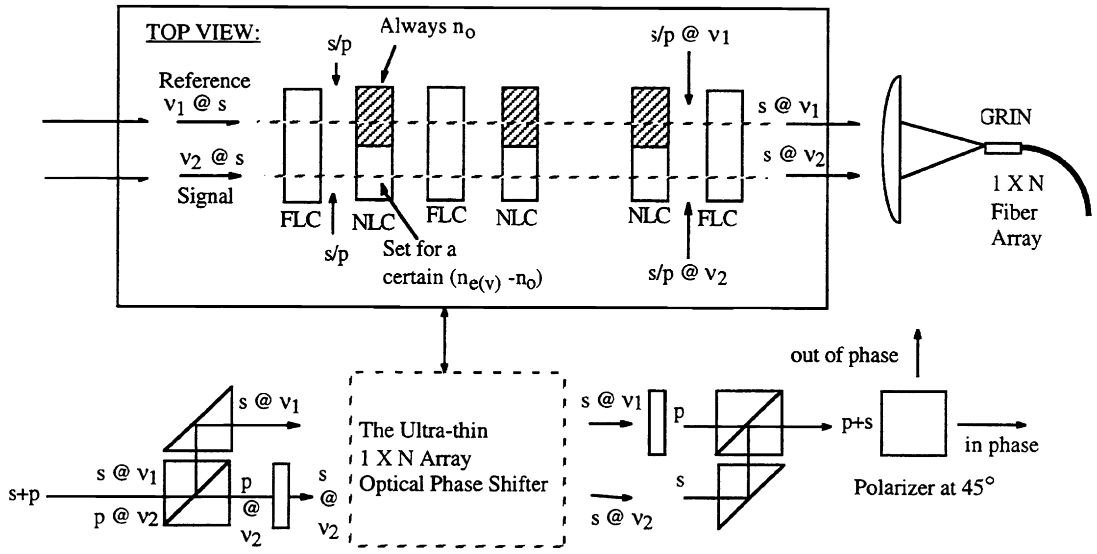


Fig.6 shows how the ultra-thin in-line phase shifter can be used in heterodyne systems such as for narrowband microwave phased array antennas. Here, the two frequency laser light fed to the module has collinear orthogonal linear polarizations.

Fig.6 shows how the ultra-thin phase shifter can be used in heterodyne systems where both the signal and reference beams have the same polarization. A top view is shown and a cylindrical lens is used to combine the signal and reference beams. Each FLC device is a 1 X N pixel array while each NLC device is a 2 X N pixel array. One NLC pixel in each of the N pairs is set to introduce ordinary index optical phase shift, while the second NLC pixel is set to give the desired electrically controlled but fixed optical phase shift. Because both signal and reference beams pass through the same FLC pixel per bit, no special biasing of the NLC cells is required.

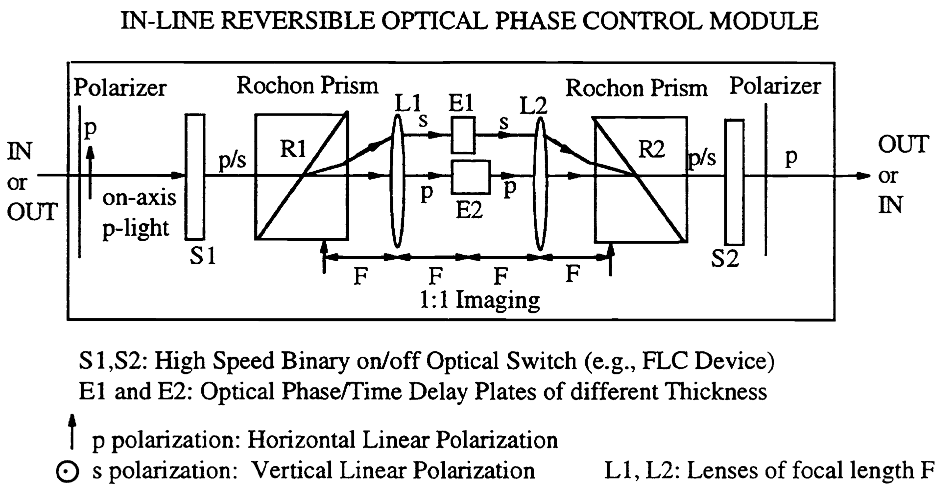
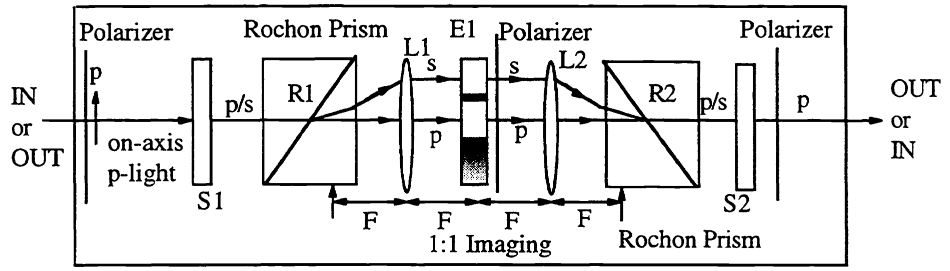


Fig.7. In-line reversible broadband optical phase shifter sub-module design based on polarizing prisms such as the Rochon prism.

Earlier, we have shown how polarizing beam displacing prisms (BDPs) can be used to form solid-optic and fiber-optic switched delay lines [16]. Fig.7. shows an in-line reversible broadband optical phase shifter sub-module design based on polarizing prisms such as the Rochon prism. N of these sub-modules are cascaded to form the N-bit optical phase shifter. Other polarizing prisms such as the Wollaston prism and Senarmont prism can also be used for this sub-modules. Typical angles for beam separation are under 20 degrees. Unlike the ultra-thin FLC-NLC optical phase shifter (Fig.5), this Rochon prism phase shifter allows for much longer optical phase/time delay settings (e.g., > 3π). This is possible using appropriately cut pieces of glass. Unlike previous in-line designs [17], the use of long length (e.g., several cms), large birefringence optical crystals is not required for our new design shown in Fig.7.

IN-LINE REVERSIBLE OPTICAL AMPLITUDE CONTROL MODULE



B1,B2: High Speed Binary on/off Optical Switch (e.g., FLC Device)
E1: 2-pixel Grey Scale Programmable Linear Polarization Rotator (e.g., Parallel-rub Birefringent Mode or Twisted NLC Device)

L1, L2: Lenses of focal length F

p polarization: Horizontal Linear Polarization
s polarization: Vertical Linear Polarization

Fig.8. In-line reversible broadband optical attenuator sub-module design based on polarizing prisms such as the Rochon prism.

Fig.8. shows an in-line reversible broadband optical amplitude control sub-module design similar to the optical phase shifter sub-module in Fig.7.Here, the preprogrammed optical phase/time delay plates between the lens pair are replaced by preprogrammed linear polarization rotators and a polarizer. Again, N of these sub-modules are cascaded to form a N-bit optical amplitude control module.

6. ALL SOLID-OPTICAL ADAPTIVE PHOTONIC CONTROL MODULES

Earlier, we have characterized the issues dealing with fiber array coupling optics such as fiber GRIN lens-based coupling for phased array applications [18]. We experimentally showed that for direct GRIN--free space/solid optics path-GRIN coupling, optical losses are very small (e.g., <0.2 dB) if the free-space path is < 5 cm. In some cases, longer GRIN-GRIN paths are required, and we have experimentally shown that imaging optics must be used to maintain the same low loss level achieved for < 5 cm distances. In the section to follow, we introduce yet another novel GRIN-GRIN optical coupling concept that serves the intermediate (e.g., 15 cm) optical path length designs where low power adaptive optics are sufficient for low loss coupling.

Ultracompact sub-modules can be formed using all solid-optics, as shown in Figures 9 and 10. These designs provide higher robustness optical beam amplitude and phase/time delay sub-modules using both bulk-optics such as cube PBSs and GRIN fiber lenses, and thin-film optics such as QWPs, mirrors, high speed on/off optical switches, and grey-scale programmable linear polarization rotators. By using all four faces of the cube PBS for thin-film optics placement, a high optical beam stability design in terms of beam alignment can be implemented, particularly with the placement of the two birefringent thin-film optics adaptives lenses. Note that one lens acts on the p-polarization while the other lens acts on the s-polarization. Any fixed or programmable birefringent film can be used to form these adaptive lenses required per sub-

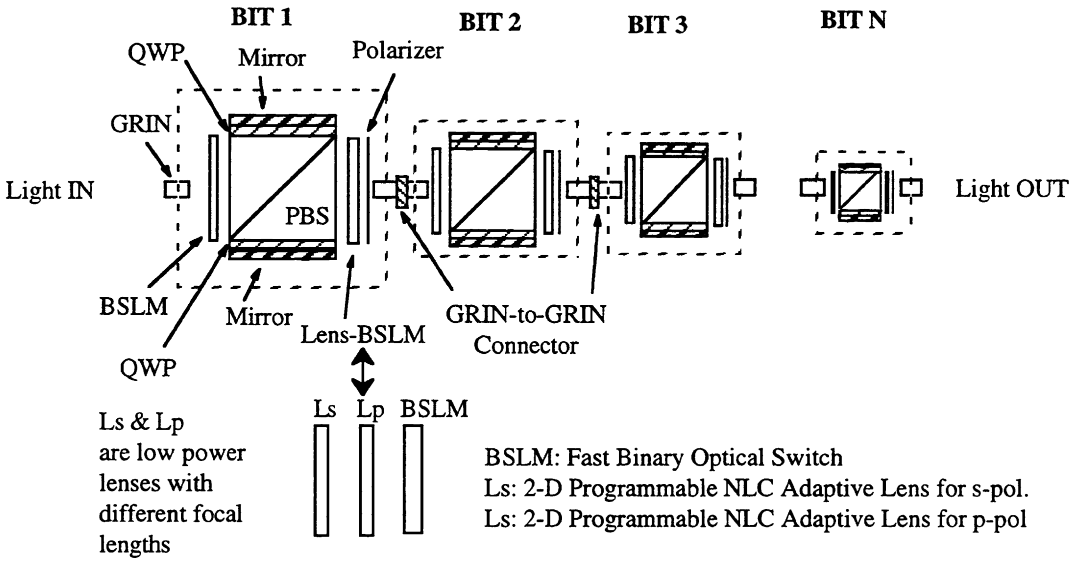


Fig.9 shows how solid-optics sub-modules with adaptive beam coupling can be cascaded to form a robust N-bit optical phase/time delay module.

Amplitude Control Sub-Module

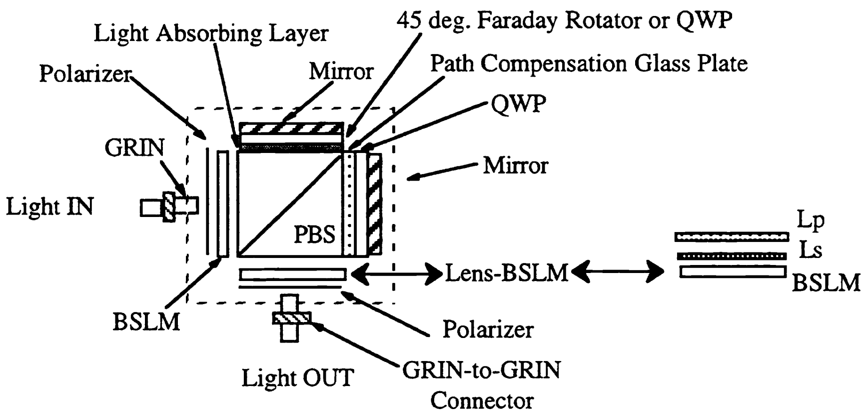


Fig.10 shows a solid-optics amplitude control sub-module with adaptive beam coupling. This sub-module can be cascaded to form a robust N-bit optical amplitude control module.

module. One excellent choice for these lenses is the use of electrically programmable parallel-rub birefringent-mode NLC lenses [19-20]. These lenses are low optical power adaptive lenses with very fine optical beam modification capabilities, and hence fit our sub-module fiber adaptive optical coupling application. These sub-module design features ensure a low optical loss, high mechanical stability sub-module package. To obtain optical phase/time delay, the natural geometry and physical size of the cube are exploited. The specific size of the cube PBS determines the phase/time delay characteristics of the sub-module. Today, commercial PBS cube sizes are typically less than 5 cm per side. In this case, one beam travels 10 cms more than the other switched optical beam. Because the beam travel is in solid-optics and not free-space, a greater delay is achieved for the same travel distance. By appropriately cascading various cube size sub-modules, a N-bit optical control module can be formed. Note that for a maximum 5 cm side cube, the straight beam travels 5 cm and hence efficient low loss GRIN-GRIN coupling can be achieved without the Lp adaptive thin lens. On the otherhand, the reflected path beam travels 15 cm, and in this case, the Ls adaptive thin lens is important and provides the low loss coupling. Hence, for sub-modules using > 5 cm side cubes, both Lp and Ls adaptive thin lenses must be used in the module. For < 5 cm side cubes, only the Ls adaptive thin lens is required per module.

To obtain N-bit optical beam amplitude control using similar solid and thin-film optics, a minor change in the optical beam flow path in the phase sub-modules is required. This change (see Fig.10) results in the required symmetric beam flow, giving no relative time delay per submodule. The previous sub-module designs provide independent optical beam amplitude and phase/time delay control. By cascading these amplitude and phase/time delay sub-modules, both optical beam amplitude and optical phase/time delay control are possible. An important application for this high speed module is adaptive null steering for phased array systems, where both amplitude and phase/time delay control are needed.

7. MODULE SWITCHING SPEED REQUIREMENTS FOR BEAM SCANNING

Bit 3 Switch 3	Bit 2 Switch 2	Bit 1 Switch 1
OFF	OFF	OFF
OFF	OFF	ON
OFF	ON	OFF
OFF	ON	ON
ON	OFF	OFF
ON	OFF	ON
ON	ON	OFF
ON	ON	ON

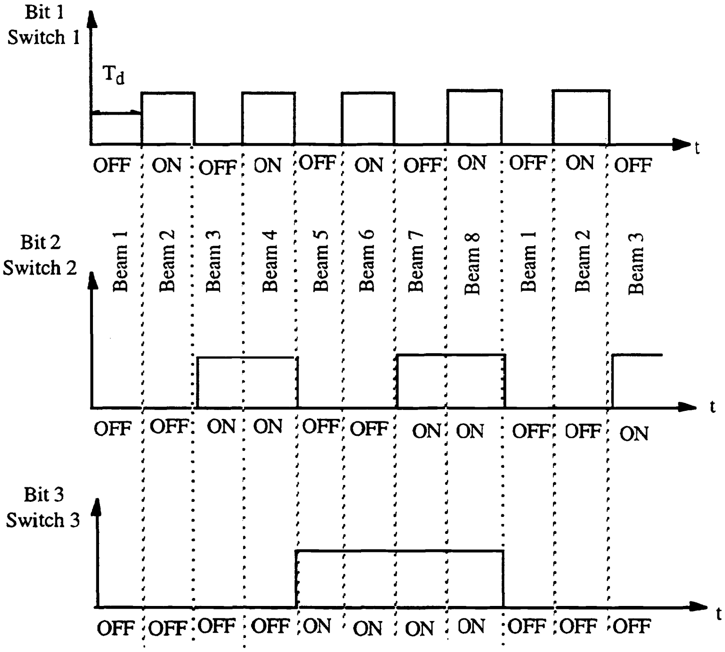


Fig.12 shows the different on/off switching rate requirements for the binary phase/time delay sub-modules that form a 3-bit optical delay line for antenna beam scanning.

Most phased array radars follow a continuous antenna beam sweep. For instance, a radar continuously scans a 30 to 60 degree sector in azimuth. For such radars, the switching speed requirements for the different cascaded phase/time delay sub-modules is different. As shown in Fig.12, for an 8 beams scan using a 3-bit phase/time delay line, bit 1(or least significant bit) switches at a fast 1/2Td Hz rate, bit 2 switches at a slower 1/4Td Hz rate, while bit 3 (or most significant bit) switches at the slowest 1/8Td Hz rate. These rates follow the frequency in Hz of the square waves shown in Fig.12. The direct outcome of these different switching speed sub-module requirements is that the binary on/off optical switches used to make these phase/time delay sub-modules also follow the same varying switching speeds. Hence, not all sub-modules have to satisfy high switching speeds. NLC optical switches can particularly benefit from these observations as cascaded NLCs can be used to give higher switching speeds than a single NLC cell, while providing very high (> 35 dB) on/off isolations [8]. Thus, not all phase/time delay sub-modules need high switching speeds for continuous scan antennas, and hence each sub-module has to be designed to match its own speed requirements.

8. CONCLUSION

We have introduced a variety of novel N-bit, high switching speed (e.g., < 35 μs using FLCs), optical beam control modules. These modules can provide grey-scale optical amplitude and phase or ultra-short time delay control. It is important to note that because we can use one or two dimensional arrays of binary optical switches, all our modules are multi-channel, and hence can reduce overall controller cost while maximizing channel packing density. The non-collinear designs have higher channel packing density than the in-line collinear designs. Nevertheless, the in-line designs are simpler to assemble and provide greater optical signal phase stability, particularly for heterodyne-type two frequency laser systems. Solid and thin-film optics based optical beam control modules are also introduced for both amplitude and phase/time delay control. These modules employ a novel adaptive optics output beam coupling configuration using two polarization sensitive lenses that provides high optical coupling efficiency.

Applications for our N-bit optical control modules are diverse and include phase-based steering of narrowband rf phased array systems, time delay steering of very high frequency (e.g., optical, mm-wave) phased arrays, N-bit rf signal processing and transversal filtering, amplitude control of optical beams for optical and rf adaptive signal processing, beam shaping and null steering, and high speed all-optical (no optical-to-rf-optical conversion losses) N-bit optical gain equalization in wavelength, time, or code division multiple access (CDMA) fiber-optic networks. Future work relates to the experimental demonstration of these novel high speed N-bit optical beam control modules.

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